Multi-Experts Analytic Hierarchy Process for the Sensitivity Analysis of Passive Safety Systems

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Abstract: Innovative Nuclear Power Plants (NPPs) resort to passive systems to increase their safety and reliability. However, during accidental scenarios, uncertainties affect the actual behavior of passive systems. In this paper, a systematic procedure based on the Analytic Hierarchy Process (AHP) for the identification of the uncertain parameters and the propagation of their associated uncertainties is proposed. An example of application is proposed with respect to the passive Residual Heat Removal system (RHRs) of the High Temperature Reactor-Pebble Modular (HTR-PM).

Key words: Analytical Hierarchy Process (AHP), Sensitivity Analysis, Passive Safety Systems, residual Heat Removal system (RHRs), High Temperature Reactor-Pebble Modular (HTR-PM).

1. Introduction

Common to most innovative reactor concepts is the introduction of passive systems, as a complement to the standard active ones [Schulz, 2006]. Passive systems bear the advantage that their functioning rests on physical principles [Zio et al., 2009]. For their operation, these systems rely on natural forces, such as gravity or natural convection, with no need of support by external power sources as is the case for the active safety systems employed in the current and evolutionary reactor designs. Because of their nature, the magnitude of the driving forces associated to passive systems is relatively small, as compared to those driving the active systems, so that resistances (e.g. friction) can be of comparable magnitude and, thus cannot be ignored.

Furthermore, considerable uncertainties affect the parameters and factors (e.g. heat transfer coefficients and pressure losses) which determine these driving forces of passive systems and there is a strong dependence on the physical conditions and plant configuration existing at the time of action request. All these aspects significantly influence the performance of passive systems and render the problem of assessing their reliability quite a difficult one [Pagani et al., 2005; Mackay et al., 2008].

This calls for a systematic methodology for addressing all the uncertainties involved, within a rigorous, transparent, traceable, but at the same time manageable, effort of analysis.

In this paper, we resort to the application of an approach for identifying the most important system parameters to be included in a passive systems reliability assessment, which is a part of a more comprehensive methodology [Zio et al., 2003]. The approach is based on the Analytic Hierarchy Process (AHP) [Saaty, 1980]. In this work, the novelty consists in the consultation of multiple experts, who were asked to build their own hierarchies, to express their judgments on the relative importance of pairs of parameters belonging to the same level of the hierarchy and to determine the overall importance of the parameters with regards to the defined top goal. It is straightforward that different experts build different hierarchies and release different results: a comparison and integration of these is necessary and absolutely non-trivial. In this work, a qualitative approach is pursued, with reference to the identification the most important system parameters to be included in the reliability assessment of the Residual Heat Removal system (RHRs) of the High Temperature Reactor-Pebble Modular (HTR-PM) [Zhengy et al., 2008].

The paper organization is as follows. In Section 2, the basic principles underpinning the AHP method are briefly recalled. In Section 3, the main characteristics of the High Temperature Reactor-Pebble Modular (HTR-PM) and its Residual Heat Removal system (RHRs) are briefly introduced. In Section 4, the results of the application of the proposed framework for the identification of the most important parameters influencing the behavior of the RHRs of Section 3 are provided. Finally, some conclusions are drawn in Section 5.

2. The Analytic Hierarchy Process for Sensitivity Analysis

The Analytic Hierarchy Process (AHP) is here employed to provide a structured method of analysis of the thermal–hydraulic process of a passive system, so as to allow identifying the important parameters related to the target of the system design. The AHP entails three major steps [Saaty, 1980]: hierarchy structure construction to decompose the problem at hand, pairwise comparison judgment elicitation and priority vectors computation to obtain the parameters ranking [Saaty, 1980; Zio et al., 2003; Burgazzi et al., 2004].

In the following, the basic concepts of the AHP are introduced; for further details on the subject, the interested reader should consult [Saaty, 1980; Zio, 1996; Forman et al, 2001; Zio et al., 2003].

The building of the hierarchy is performed in three steps:

i. Define precisely the top goal of the hierarchy and place it at the top level.

ii. Build downward the hierarchy in different levels by putting in each level those factors directly influencing the elements of the level just above and directly influenced by the elements of the level just below. Directed arrows are placed to specify the interconnections between the elements.

iii. At the bottom of the hierarchy place the basic parameters.

The successive phase of the analysis is that of collecting pairwise importance judgments, through the following steps:

i. For each element of each level build a pairwise comparison matrix to assess the importance of the influence of the relevant entries of the level below in relation to the element under analysis. In other words, given an element k in level s, all entries of the level below, $s-1$, which affect k are compared in a pairwise fashion in terms of their relevance to k. The proper question in the pairwise comparison is of the form: ‘Considering entries X and Y of level $s-1$, how much more important is entry X compared to entry Y with respect to their influence on element k of level s?’

   The pairwise comparisons can be performed directly into a certain numerical scale or on a qualitative fashion and then translated into a numerical scale. Typically, the scale of integer numbers from 1 to 9 is used and the values a_{ij} obtained from the comparisons are organized in a square matrix.

   For example, performing qualitatively the comparison of element A with element B, the scale is the following:

1 = *A* and *B* equally important
3 = *A* slightly more important than *B*
5 = *A* strongly more important than *B*
7 = *A* very strongly more important than *B*
9 = *A* absolutely more important than *B*

By definition an element is equally important when compared to itself so the principal diagonal of the matrix is filled with ones. The appropriate reciprocals, 1/3, 1/5, . . . , 1/9 are inserted where the reverse comparison, *B* versus *A*, is required.

The numbers 2, 4, 6, 8 and their reciprocals can be used to facilitate expressing judgments for intermediate situations. In other words, the expert is allowed to resort to the use of a measure of 4, for example, when making a comparison of *A* and *B* which he believes cannot exactly be expressed by 3 nor 5;

ii. For each element *k* in level *s*, determine the potency (strength, priority, weight) $w_{i(s-1),k(s)}$ with which each element *i* in level $s-1$ affects element *k*. The priorities $\{w_{i(s-1),k(s)}\}$ of the entries *i* in level ($s-1$), relative to their importance for an element *k* in the next level (*s*) can be determined by solving an eigenvector problem. More precisely, it can be shown that given the matrix of pairwise comparisons for the element of interest, the principal eigenvector provides the vector of priorities, when normalized, and the maximum eigenvalue is a measure of consistency of the comparisons entered in the matrix [Saaty, 1980].

iii. In case of large inconsistencies in a matrix, revise its entries by redoing the judgments on the individual pairwise comparisons or by forcing the values a_{ij} to be mathematically consistent by setting them equal to w_i / w_j, where $w_i = w_{i(s\text{-}1),k(s)}$, $w_j = w_{j(s\text{-}1),k(s)}$ are the priority values of elements *i* and *j* of level *s*-1 in regards to their relevance to element *k* of level *s* immediately above. For more details on the revision process, see [Saaty, 1980].

At this point, we can compute the priority ranking of each parameter:

i. Once all the priority vectors are available, multiply them appropriately through the branches of the hierarchy (just like in a probability tree) to determine the overall weights of the bottom-level alternatives with regards to the previously defined top goal.

The major advantage of this method is that it allows for a detailed, structured and systematic decomposition of the overall problem into its fundamental components and interdependencies, with a large degree of flexibility [Saaty, 1980]. On the other hand, since the construction of the hierarchy structure and the determination of the comparison matrix are strongly dependent on the expert judgments, several experts opinions are usually used to get the conclusion and, thus, it may be more time demanding, in comparison to other sensitivity analysis methodologies.

3. The case study: HTR-PM

Starting from the gas-cooled reactor in the 1950s and advanced gas-cooled reactor in the 1960s, the high-temperature gas-cooled reactors have developed for nearly 50 years. The Chinese design of the High Temperature Gas-Cooled Reactor-Pebble bed Module (HTR-PM), which is much safer than its ancestor and other types of reactors, is based on the technology and experiences of the HTR-10 10MW high-temperature gas-cooled test reactor (HTR-10) designed in China in 2000

[Zhengy et al., 2008].

The enhanced safety of the HTR-PM is mainly due to the adoption of passive safety systems [Zhao et al., 2008]. The case study selected for the verification of the feasibility of the AHP methodology for the identification of the most relevant parameters affecting the output of a thermo-hydraulic model of a passive safety system is the Residual Heat Removal system (RHRs) of the HTR-PM. A simplified zero-dimensional description of the thermo-hydraulic evolution of the RHRs has been implemented in MATLAB and allows for the computation of the maximum outlet water temperature $T_{w,out}$ reached during the plant normal/accidental operation.

The simulation code models the following purposes of the process [Zhao et al., 2008]:

1. The residual heat radiates from the reactor vessel and other thermal sources to the water in the water-cooled wall;
2. Because of the difference in temperature, natural convection will set up through water, in the water-cooled wall and pipes connected with the air-cooled heat exchanger: then heat will transfer to the water side of the heat exchanger;
3. The heat will transfer by thermal conduction from the water side to the air side of the heat exchanger, due to the difference of temperature;
4. As the air-cooled heat exchanger is located in the air-cooled tower, natural convection of air will set up, and take heat to the final heat trap–atmosphere.

Figure 1 shows the specific equipments structure of one of the 3 loops of the RHRs of the HTR-PM. The water-cooled wall get the heat from the reactor vessel by thermal radiation. Then the pipe transfers the water to the air-cooled heat exchanger which is situated in the air-cooled tower. The air takes the heat away from the heat exchanger to the environment.

The MATLAB model relies on the adoption of 37 parameters that are listed in Table 1 together with their corresponding probabilities of occurrence defined on the basis of previous experience and/or information obtained by skilled experts.

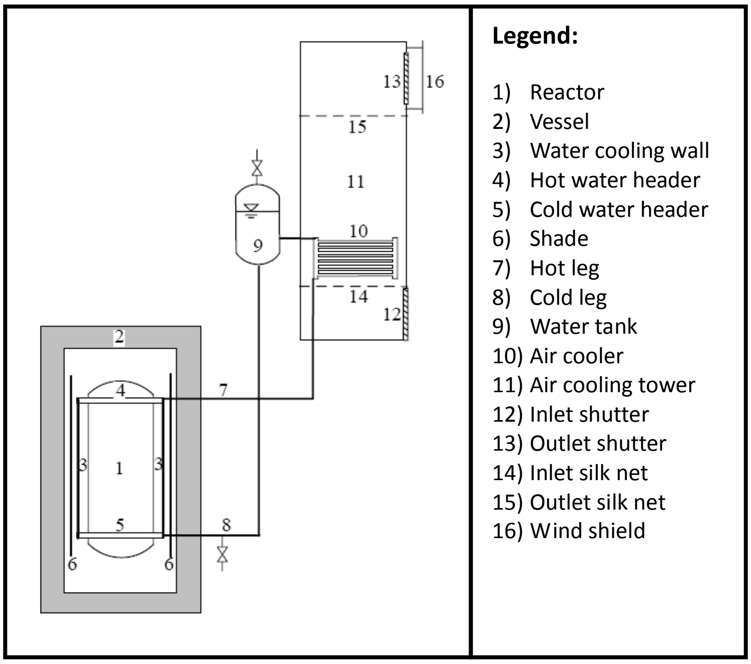


Figure 1 Sketch of RHRs in HTR-PM

N	*Parameter*	*Distribution*	*Note*
1	W	Normal	Residual heat power
2	$T_{a,in}$	Bi-Normal	Temperature of inlet air in the air-cooled tower
3	x_{i1}	Uniform	Resistance coefficient of elbow
4	x_{i2}	Uniform	Resistance coefficient of header channel
5	x_{iw}	Uniform	Resistance coefficient of the water tank walls
6	$x_{ia,in}$	Uniform	Sum of the resistance coefficients of inlet shutter and air cooling tower and silk net
7	$x_{ia,out}$	Uniform	Sum of the resistance coefficients of outlet shutter and air cooling tower and silk net
8	$x_{ia,narrow}$	Uniform	Resistance coefficient of the narrowest part of the tower
9	$P_{a,in}$	Uniform	Pressure of the inlet air in the cooler tower
10	dx	Uniform	Roughness of pipes
11	H_a	Normal	Height of chimney
12	L_a	Normal	Length of pipes in the exchanger
13	N_a	Normal	Total number of pipes in the air cooler
14	A_f	Normal	Air flow crossing are in the narrowest part of the tower
15	$A_{f,in}$	Normal	Inlet air flow crossing area in the tower
16	$A_{f,out}$	Normal	Outlet air flow crossing area from the tower
17	$A_{f,narrow}$	Normal	Crossing area in the narrowest part of the tower
18	S_1	Normal	Distance between centers of adjacent pipes in horizontal direction
19	S_2	Normal	Distance between centers of adjacent pipes in vertical direction
20	S	Normal	Distance between fins in the ribbed pipe
21	D_a	Normal	Pipes inner diameter in the air cooling exchanger
22	D_o	Normal	Pipes outer diameter
23	D_{outer}	Normal	Rib outer diameter
24	P_w	Normal	Water pressure in the pipes
25	H_w	Normal	Elevatory height of water
26	N_w	Discrete Normal	Number of water cooling pipes for each loop
27	L_w	Normal	Length of the water cooling pipes
28	D_w	Normal	Inner diameter of the water cooling pipes
29	D_1	Normal	Inner diameter of the in-core and air cooler connecting pipes
30	D_2	Normal	Inner diameter of the in-core header
31	L_C	Normal	Length of the in-core and air cooler connecting pipes (“cold leg”)
32	L_H	Normal	Length of the in-core and air cooler connecting pipes (“hot leg”)
33	R_i	Log-normal	Thermal resistance of pipes inside of the heat exchanger
34	R_o	Log-normal	Thermal resistance due to the dirt of the pipes fins
35	R_g	Log-normal	Thermal resistance of the gap between fins
36	R_f	Log-normal	Thermal resistance of fins
37	$lamd$	Normal	Heat transfer coefficient of the pipes

Table 1 Parameters which are regarded relevant for the behavior of the passive RHRs

4. Results

Considering the RHRs illustrated in Section 3, a set of 3 hierarchies of s=3 levels connecting the top goal representing the system mission of power removal to the basic parameters of the system model were developed by three experts (Figures 2-4). Obviously, the proposed hierarchies do not pretend to be the only ones possible, since the definition and decomposition of the structure is flexible and dependent on the problem and on the viewpoint adopted. The three experts, who were asked to build the hierarchies, are all involved in the design phase of the whole HTR-PM; they were also asked to express their judgments on the relative importance of pairs of parameters belonging to the same level of the hierarchy, by filling in appropriate comparison matrixes associated to the hierarchy, and to determine the overall weights of the bottom-level alternatives with regards to the defined top goal. The top goal of the hierarchy (level s=3) has been set as the removal of the core decay power to the RHR system. The AHP-decomposition of the problem was purposely devised so as to lead to small-size matrices so to keep the analysis manageable and reduce the danger of inconsistencies in the entries to the matrices (in the application, any inconsistency encountered was eliminated by forcing mathematical consistency as explained in Section 4, so not to change the priority rankings).

The great advantage of the hierarchical approach adopted is that it forces the analyst to consider in a structured and systematic way all the processes involved, the governing parameters and their relations. This should ensure completeness of the analysis, so that no relevant processes or parameters are missed and their relations are not misunderstood or underestimated.

In what follows, the results provided by the three different experts are analyzed.

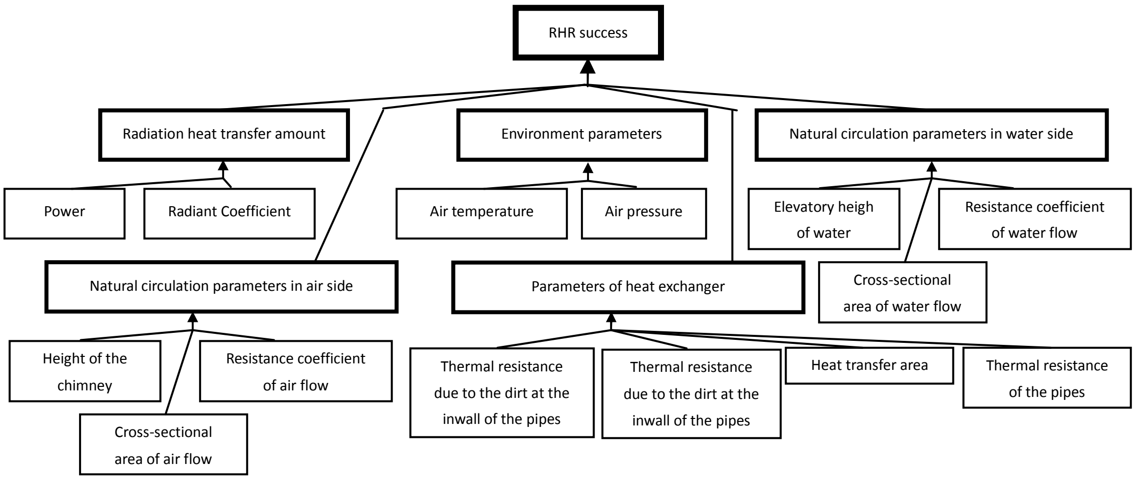


Figure 2 Hierarchy structure given by expert 1

In the analysis run by the first expert, k=5 important factors have been identified in the power transfer process and constitute the first level of the hierarchy, directly influencing the top goal of power removal (Figure 2): the radiation heat transfer amount, the natural circulation parameters affecting the air side and those affecting the water side, the environment parameters and the parameters related to the structure of the heat exchanger. For each of the five elements of the level s=2 of the hierarchy, the task of power transfer is affected by few (two to four) independent factors. The level s=1 of the hierarchy is composed of these items, which affect each element of the level s=2 immediately above. Table 2 reports the priorities resulting from the pairwise comparisons assigned by the first expert to the first-level elements of the passive system under analysis. According to expert 1 judgment, it is easily seen that the power W and the temperature of air in the air-cooled tower $T_{a,in}$ have been considered absolutely the most important parameters.

Parameter	Priority
Power	0.43
Radiant coefficient	0.086
Air temperature	0.24
Air pressure	0.034
Elevatory height of water	0.018
Cross-sectional area of water flow	0.018
Resistance coefficient of water flow	0.0035
Elevatory height of air	0.047
Cross-sectional area of air flow	0.047
Resistance coefficient of air flow	0.016
Thermal resistance due to the dirt at inwall of the pipes	0.014
Thermal resistance due to the dirt at outwall of the pipes	0.0046
Thermal resistance of pipes	0.0079
Heat transfer area	0.038

Table 2 Priorities of the basic parameters at the bottom level of the hierarchy according to expert 1 judgment

The other 2 experts, through the use of the AHP, have drawn different conclusions regarding the identification of the relevant parameters which affect the accomplishment of the power removal target by the passive RHRs. They have identified a different hierarchy to decompose the problem and, thus, their pairwise comparison judgments regarding the relevance of the considered parameters has lead to a different computation of priority vectors to obtain their ranking. Figures 3 and 4 show the hierarchies built by the second and third experts, respectively; Tables 3 and 4 report the priorities resulting from the associated pairwise comparisons.

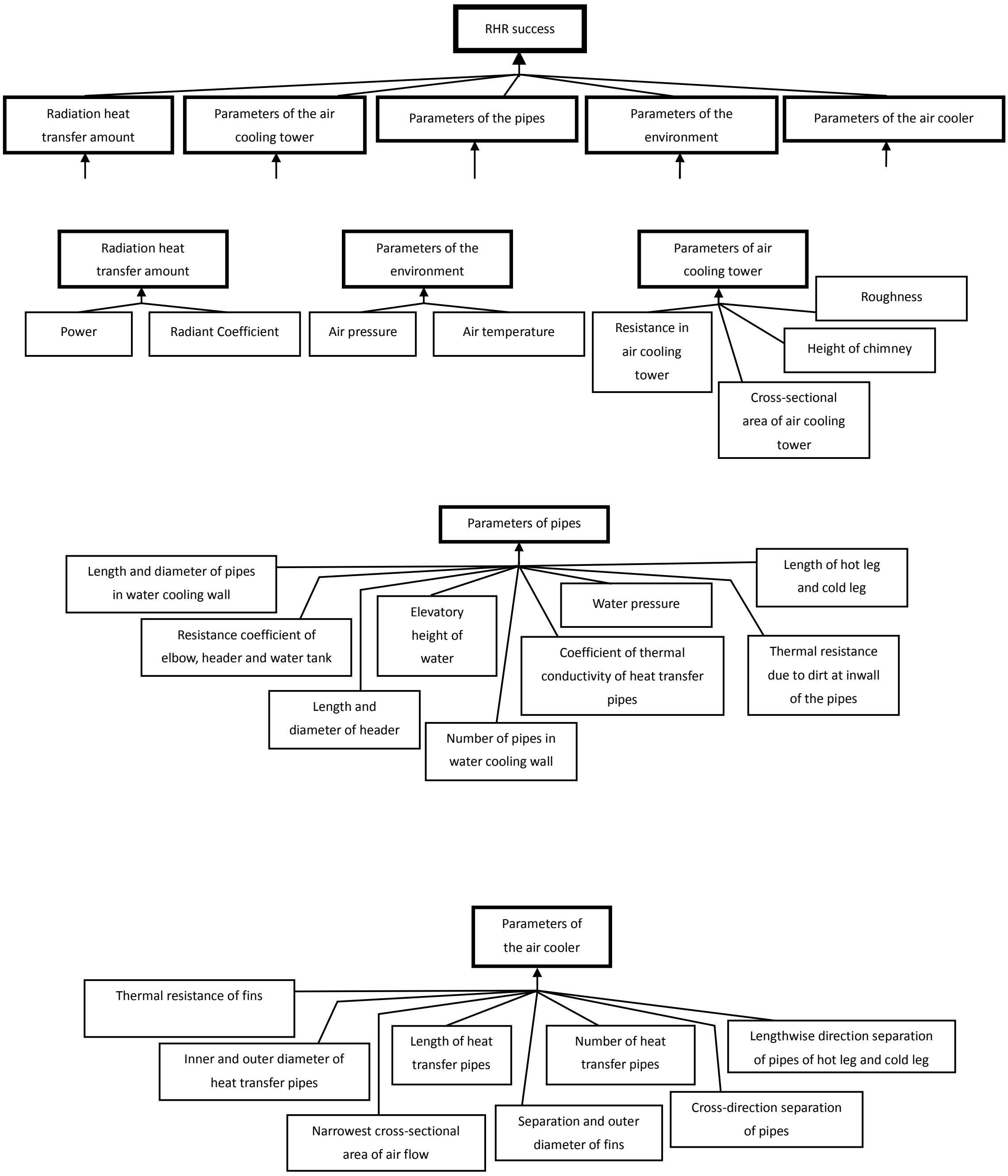
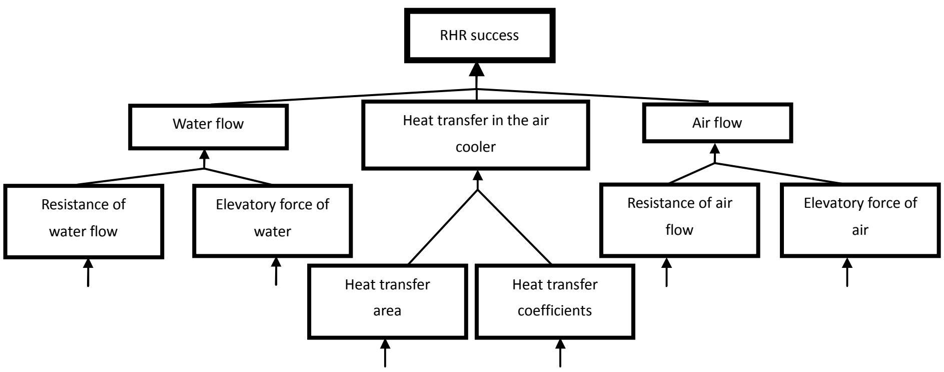
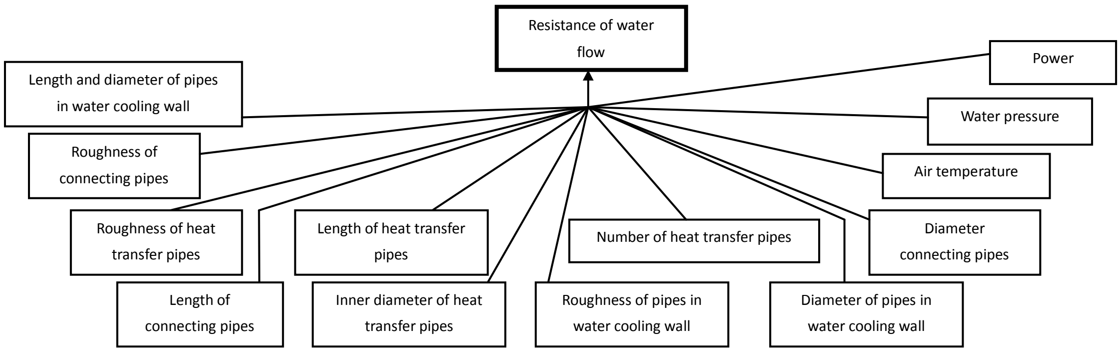
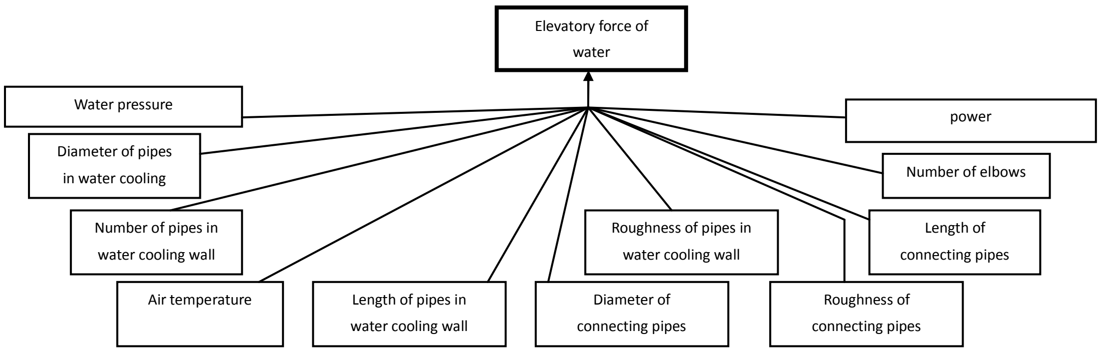
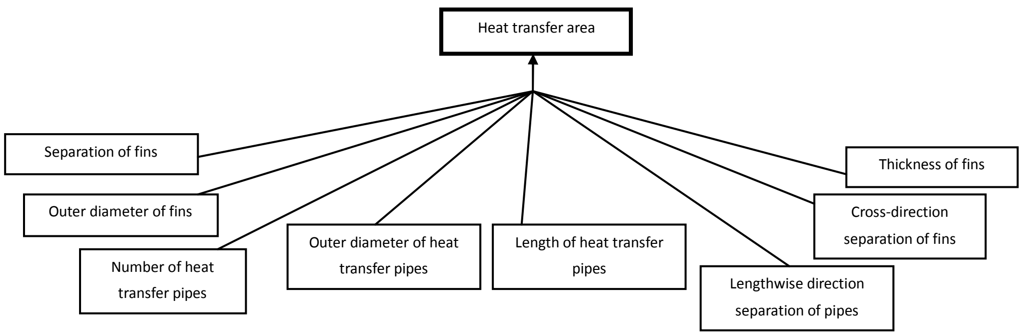


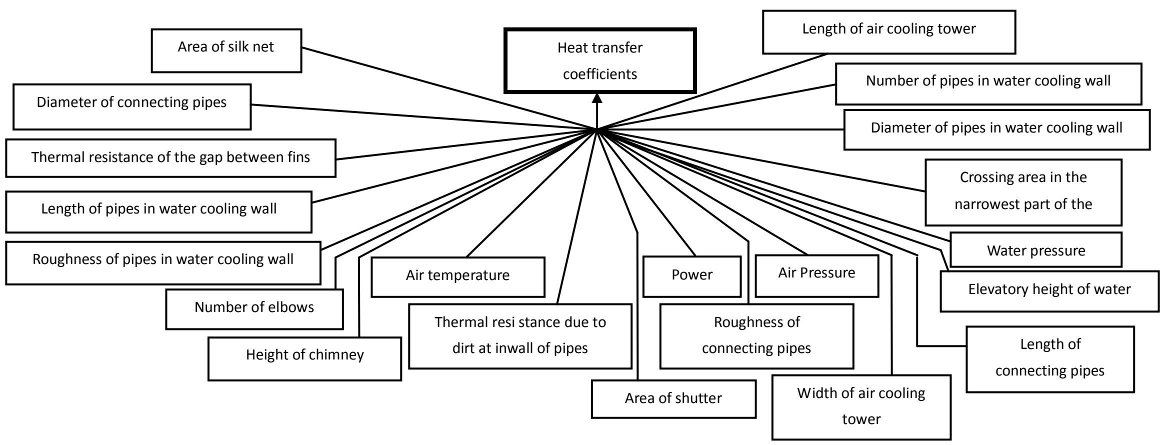
Figure 3 Hierarchy structure given by expert 2

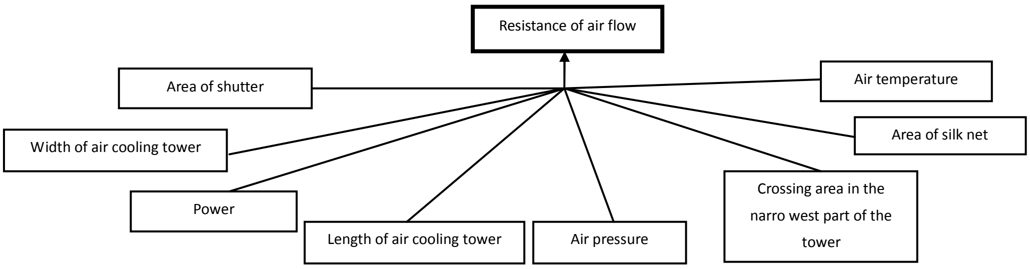



Resistance of water flow
Power
Length and diameter of pipes in water cooling wall
Water pressure
Roughness of connecting pipes
Air temperature
Roughness of heat transfer pipes
Length of heat transfer pipes
Number of heat transfer pipes
Diameter connecting pipes
Length of connecting pipes
Inner diameter of heat transfer pipes
Roughness of pipes in water cooling wall
Diameter of pipes in water cooling wall


Elevatory force of water
Water pressure
power
Diameter of pipes in water cooling
Number of elbows
Number of pipes in water cooling wall
Roughness of pipes in water cooling wall
Length of connecting pipes
Air temperature
Length of pipes in water cooling wall
Diameter of connecting pipes
Roughness of connecting pipes


Heat transfer area
Separation of fins
Thickness of fins
Outer diameter of fins
Cross-direction separation of fins
Number of heat transfer pipes
Outer diameter of heat transfer pipes
Length of heat transfer pipes
Lengthwise direction separation of pipes


Heat transfer coefficients
Length of air cooling tower
Area of silk net
Number of pipes in water cooling wall
Diameter of connecting pipes
Diameter of pipes in water cooling wall
Thermal resistance of the gap between fins
Crossing area in the narrowest part of the
Length of pipes in water cooling wall
Water pressure
Roughness of pipes in water cooling wall
Air temperature
Power
Air Pressure
Elevatory height of water
Number of elbows
Thermal resi stance due to dirt at inwall of pipes
Roughness of connecting pipes
Height of chimney
Length of connecting pipes
Area of shutter
Width of air cooling tower



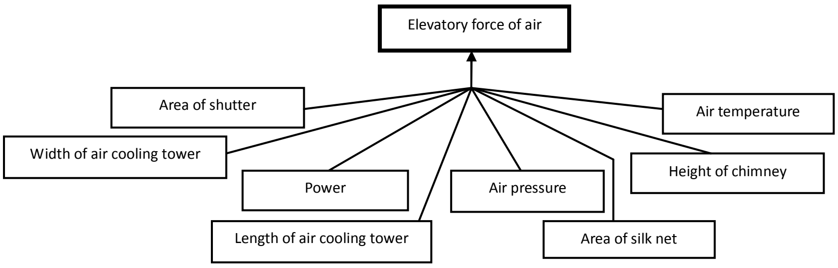


Figure 4 Hierarchy structure given by expert 3

Parameter	Priority
Power	0.38
Radiant coefficient	0.042
Air temperature	0.18
Air pressure	0.088
Height of chimney	0.065
Roughness	0.019
Resistance in air cooling tower	0.022
Cross-sectional area of air cooling tower	0.055
Length and diameter of pipes in water cooling wall	0.0067
Elevatory height of water	0.019
Water pressure	0.0022
Length of hot leg and cold leg	0.0046
Length and diameter of header	0.0031
Resistance coefficient of elbow, header and water tank	0.0015
Coefficient of thermal conductivity of heat transfer pipes	0.014
Number of pipes in water cooling wall	0.0097
Thermal resistance due to dirt at inwall of the pipes	0.0011
Thermal resistance of fins	0.0069
Length of heat transfer pipes	0.032
Number of heat transfer pipes	0.014
Lengthwise direction separation of pipes	0.0032
Cross direction separation of pipes	0.0047
Separation and outer diameter of fins	0.016
Narrowest cross-sectional area of air flow	0.0023
Inner and outer diameter of heat transfer pipes	0.010

Table 3 Priorities of the basic parameters at the bottom level of the hierarchy according to expert 2 judgment

Parameter	Priority
Power	0.17
Length of pipes in water cooling wall	0.016
Diameter of pipes in water cooling wall	0.024
Number of pipes in water cooling wall	0.018
Roughness of pipes in water cooling wall	0.0084
Length of connecting pipes	0.035
Diameter of connecting pipes	0.073
Number of elbows	0.053
Roughness in connecting pipes	0.0097
Water pressure	0.0090
Air temperature	0.013
Inner diameter of heat transfer pipes	0.011
Length of heat transfer pipes	0.021
Number of heat transfer pipes	0.038

Roughness of heat transfer pipes	0.0030
Elevatory height of water	0.084
Outer diameter of heat transfer pipes	0.059
Cross direction separation of pipes	0.020
Lengthwise direction separation of pipes	0.020
Outer diameter of fins	0.039
Thickness of fins	0.010
Separation of fins	0.031
Thermal resistance due to dirty at inwall of the pipes	0.015
Thermal conductivity resistance of heat transfer pipes	0.015
Thermal resistance due to dirt of the fins	0.013
Thermal resistance of the gap between fins	0.012
Width of air cooling tower	0.024
Length of air cooling tower	0.023
Crossing area in the narrowest part of the tower	0.023
Area of silk net	0.023
Area of shutter	0.023
Air pressure	0.0055
Height of chimney	0.061

Table 4 Priorities of the basic parameters at the bottom level of the hierarchy according to expert 3 judgment

Regarding the priority values reported in Tables 2-4, it should be pointed out that several methods exist to tackle the issue of inter-expert variability and aggregation of priorities provided on the same hierarchy structure. In this work, the aggregation of the judgments of the different experts has not been performed: this aspect of the problem is beyond the scope of the work presented here, so that only general conclusions on the importance of the parameters will be drawn, in qualitative terms, on the basis of simple comparisons. It is relevant to note that the decomposition offered by different hierarchies allows to identify the sources of discrepancy among experts in a transparent way. In any case, a future phase of our work will regard the investigation on the opportunity to aggregate priorities provided on the basis of different structures.

The conclusions that can be drawn from the analysis of the priority values is that the power W is the parameter of the system regarded as most important for the operation of the passive system. It can also be seen that two experts consider the temperature of air in the air-cooled tower $T_{a,in}$ as the second most important influencing parameter; however, a large discrepancy exists in the judgment of the role of $T_{a,in}$, with experts 1 and 2 considering it as important as W, while according to expert 3 it is of much less importance. Still, it seems that $T_{a,in}$ can be generally ranked secondary to W, but more important than the water pressure in the pipes P_w, which, according to expert 1, is regarded of approximately equal importance to W and $T_{a,in}$.

The relevance of the above mentioned parameters receiving high rankings can be understood on a physical ground, since P_w and $T_{a,in}$ determine the thermal–hydraulic conditions of the heat exchange process. Likewise, W is crucial to the operation of the system as it indicates the amount of energy that is to be removed from the core.

In addition, it turns out that, in spite of the discrepancies in the experts priority values of the highest-ranked parameters, a wider agreement is obtained over the less important ones (e.g., obstructions and fouling).

In this respect, further conclusions can be drawn when simultaneously considering the priorities values of plant configuration parameters (e.g., power W, number of pipes in the air cooler N_a, number of water cooling pipes for each loop N_w, etc..), physical condition parameters (e.g., water pressure in the pipes P_w, temperature of air in the air-cooled tower $T_{a,in}$ and inlet pressure of the air in the air cooler tower $P_{a,in}$, etc..), and resistance parameters (e.g., thermal resistance of pipes inside of the heat exchanger R_i and thermal resistance due to the dirt of the pipes fins R_o, etc…). All the experts agree that the group of resistance parameters has a minor impact, in relative terms, in comparison to the physical and plant configuration parameters, on the functioning of the passive system with respect to the effects on the maximum outlet water temperature $T_{w,out}$ reached.

These considerations can serve as a basis for the selection of those least relevant parameters that could be omitted from the successive detailed probabilistic analysis of the system performance by means of best-estimate codes [Di Maio et al., 2010].
Finally, the relative rankings of the 37 parameters of Table 1 can be compared with those resulting from the Sensitivity Analysis based on the Variance Decomposition Method, performed in [Yu et al., 2010]: the results of the AHP analysis have turned out to be in general different, albeit in some cases similar, from the selection of the important parameters of [Yu et al., 2010].

5. Conclusion and Discussion

In this paper, the AHP method has been employed to select the important parameters driving the behavior of the RHRs in the HTR-PM. Three experts have constructed the hierarchy and delivered determined the associated judgment matrix independently. A qualitative comparison of the different priority values given by different experts has been done to synthesize the results of the analysis.
In conclusion, the analysis seems to provide a relevant tool applicable a priori to systematically guide the selection of the relevant parameters to be selected for performing the best-estimate code runs of the passive system reliability assessment.
As a drawback, the dependence of the results on expert judgment requires that this approach to parameters selection be supported and integrated by quantitative sensitivity analysis techniques whose results may serve for critically analyzing, and possibly confirming, the findings of the AHP procedure, with feedback to the experts in support of a possible revision of their judgments.

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